Canadian Science Publishing | Canadian Journal of Plant Science

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Journal:	*Canadian Journal of Plant Science*
Manuscript ID	CJPS-2019-0223.R3
Manuscript Type:	Article
Date Submitted by the Author:	17-Feb-2020
Complete List of Authors:	Pittman, Tyler; Princess Margaret Hospital Cancer Centre, Biostatistics Department
Keywords:	grain yield, fertilizer, precision agriculture, case study (observational)
Is the invited manuscript for consideration in a Special Issue?:	Not applicable (regular submission)

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Too much fertilizer? An observational association between inputs at planting and crop yield on a Saskatchewan farming operation

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Received 23 August 2019. Revised 17 February 2020.

Abstract: Grain yield and its variability is a major driver of seeding rate and inorganic fertilizer use at planting among grain growers. Recommended rates for fertilizer application with regard to crop utilization and soil management are discretionary and vary between producer and agronomist. This observational case study with Bayesian inference examines the association between application rates of: inorganic nitrogen, phosphorus, potassium chloride and sulphur at planting and yield of: durum wheat (*Triticum turgidum* L.), large green lentil (*Lens culinaris* Medik.), canola (*Brassica napus* L.), canaryseed (*Phalaris canariensis* L.) and spring barley (*Hordeum vulgare* L.). Utilizing precision agriculture, input and crop yield information for each parcel of cultivated land was collected over a four-year period from 2015 to 2018 on a continuous no-till farming operation in the semi-arid region of Saskatchewan, Canada. Hierarchical models were derived that accounted for yield variability in crop types due to the random effects of: field, cultivar, crop planted in previous year, planting year, combine machine, observation location within field and elevation. Evidence from this longitudinal study suggests that seed-placed fertilizer above the recommended safe rate can be associated with yield decline on farming operations in the semi-arid environment of Saskatchewan, Canada.

Key words: grain yield, fertilizer, precision agriculture, case study (observational)

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Introduction

Adaptation in seed and fertilizer rates utilized at planting are traditional methods of augmenting grain yield in conventional farming (May et al. 2012). In Canada, use of inorganic fertilizer for the growing of cereal crops has increased substantially since the 1980s (Yang et al. 2007). Much of this upsurge is attributable to maximizing food production for an expanding global population (Ladha et al. 2005), and the implementation of farming routines that have eliminated fallow periods in subsequent growing seasons (Grant et al. 2016). Crop rotation is another practice advocated to increase yield potential from available soil nutrients (Gan et al. 2003), and to impede plant pests that decrease yield (Bainard et al. 2017). In particular, rotations that incorporate pulses to supplant wheat have been advocated to reduce the risk of *Fusarium* (Cruz et al. 2012). More recently, interest has advanced in management strategies with remedial fertilizer application to replenish depleted soil nutrients (Grant and Flaten 2019).

There is concern about the long-term sustainability of repeated fertilizer application to optimize crop yield (Wei et al. 2016). Without fertilizer additives, removal of nutrients from the soil can exceed the amount being replaced through continuous cropping (Bedada et al. 2014). Prior to, or in lieu of the adaptation of continuous cropping on the semi-arid prairie region, summer fallow was practiced (Bainard et al. 2017). In this cropping system, tillage is exercised to control weeds on fallow ground; a variation known as chem-fallow applies herbicide to manage weed and crop growth, which conserves soil moisture (Anderson 2010). The advent of no-tillage farming through direct-seeding has become prevalent over the past two decades on the Canadian Prairies, and is associated with elevated soil mineralization of nitrogen and organic matter (Grant et al. 2016). Further advancement in fertilizer management has been made with adoption of precision agriculture. Utilizing location, variable rate fertilization allows producers

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to allocate crop inputs to management zones within a field with the most desirable attributes to maximize yield potential (Beckie et al. 1997).

Inorganic fertilizer blends are commonly utilized in the planting of cereal and broadleaf crops in the prairie region of Canada with direct-seeding systems (Beckie et al. 1997). Nomenclature of commercially available blends denotes mixed ratio content of: nitrogen (N), phosphorus (P), potassium chloride (KCl) and sulphur (S) per a given unit. Each of these components comprise a macronutrient that is utilized for plant growth (Zhang et al. 2016). Fertilization by nitrogen is associated with increased plant height and grain yield (May et al. 2012). Phosphate fertilization can also increase yield, although there is concern that application made at planting may be underutilized (Grant et al. 2002). For some wheat cultivars, excess residual phosphorus has been associated with decreased grain yield (Deng et al. 2018). Potassium is associated with grain quality and yield (Mohr et al. 2004). Residual soil potassium tends to be found in much higher amounts than other macronutrients on the Canadian Prairies (May et al. 2012). The addition of sulphur at planting is done to improve plant development in cereals (Hrivna et al. 2015), and to enhance yield of canola crops (Karamanos et al. 2007).

Adherence to safe application rates for the amount of fertilizer placed in row with seed is of consideration. Nutrient requirements for crop development sometimes exceeds the safe rate, and deficient soil fertilization may result if placement in the seed row is the only option for the producer (Grant and Flaten 2019). With regard to Saskatchewan soils, the maximum recommended application rate for phosphorus placed with seed is roughly: 22.4 kg ha^{-1} for lentil, 28.0 kg ha^{-1} for canola, 33.6 kg ha^{-1} for canaryseed and 56.0 kg ha^{-1} for cereal crops (Agriculture Knowledge Centre 2019a). Maximum safe application rates of potassium with seed is similar to that for phosphorus; however, the combined application amount for potassium and phosphorus

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should not exceed the maximum safe application rate for phosphorus (Agriculture Knowledge Centre 2019b). In some soils, less than 15 kg ha^{-1} of nitrogen may be safely placed with cereal or canola seed in the seed row (Agriculture Knowledge Centre 2019c), although higher amounts (up to 200 kg ha^{-1}) are permitted between seed rows with mid-row banding (Karamanos et al. 2007) and side-row banding (May et al. 2008). Seed-placed sulphur should not exceed 22.4 kg ha^{-1} for canola (Agriculture Knowledge Centre 2019c).

Other determinants of grain yield beside fertilizer application include seeding rate (May et al. 2012), and row spacing (Lafond 1994). In pulse crops, liquid, powdered peat, or granular forms of Rhizobium inoculant are used to promote biological nitrogen fixation and reduce the requirement for supplemental inorganic nitrogen fertilization (Rice et al. 2000). Biologically-fixed nitrogen is more readily utilized by plants and less susceptible to leaching, which is a concern in semi-arid environments (Hossain et al. 2017). Spatial factors also have an effect on grain yield in a given crop year. These consist of variability in soil productivity due to attributes such as topography, drainage and ambient soil type (Beckie et al. 1997). Climatic conditions such as temperature and rainfall during a growing season also influence crop yield (Hopkins 1935), as does recommended seeding rate (Lafond 1994).

The objective of the present study is to examine the association between modifiable amounts of inorganic nitrogen, phosphorus, potassium chloride and sulphur at planting with grain yield for five crop types as observed on a Saskatchewan farming operation. It is hypothesized that, (i) the current mean rate of seed and fertilizer utilized at planting is advisable for some crops; and (ii) evidence of redundant fertilizer application will be ascertained for other crops.

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Materials and Methods

Observation site

The observational study was conducted at a farming operation approximately 60 km NNW of Swift Current in the southwestern region of Saskatchewan, Canada. Rainfall data for each weather event that occurred between 2015 and 2018 was collected at a dwelling close to the geographic center of the farming site. To construct a climate history, temperature data was obtained from an automatic weather station in Swift Current (Environment Canada 2019). Precipitation for this location was highly variable; cumulative rainfall from April to November varied from a low of 139 mm in 2018 to a high of 515 mm in 2016 (Fig. 1). The mean annual temperature was 4.6 °C. Over the study period, an extreme maximum temperature of 39.8 °C and an extreme minimum temperature of -36.8 °C were observed.

Each year of study encompassed approximately 1,740 seeded hectares from 31 disjoined fields (Fig. 2). Fields ranged from 16.0 to 96.0 hectares in area. Elevation varied from 621.2 to 675.4 meters, with a mean of 649.9 meters. Soil type for the entire farming operation is classified as vertisolic (Anderson 2010), on a base of lacustrine clay (Harington 2017).

Cropping practice

The farming system was strictly rain-fed grain production with continuous no-till cropping. Durum wheat and large green lentil were the two major crops cultivated. Additional crops used in rotation included: canola, canaryseed and spring barley. Variable rate seeding and fertilization was applied for some fields, and a uniform application to others. Management zones that utilized variable rate farming were created from quintiles of the yield data from previous crop years, starting in 2014. The decision to implement variable rate or uniform application was

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operator driven, as well as the amount of variation permitted in rate application. Commercially obtained compounds used for all fertilization events consisted of a blend of: urea (N), monoammonium phosphate (P), potassium chloride (KCl) and ammonium sulphate (S).

The rotation of crops by year for field is shown in Table 1; a list of crop cultivars and fertilizer blends utilized is presented in Table 2. Direct-seeding with no-till management was employed with 30 cm row spacing between seed furrows. The seeding equipment utilized auto-sectional control to disengage seed runners and minimize double seeding. Seeding depth was approximately 2.5 cm for canola, and 3.8 to 5.1 cm for the other crops. On the seed drill, 8600 kPa packing pressure was used with 1.9 cm hoe-type furrow openers per seed row. Fertilizer containing large amounts of nitrogen (41-0-0-4 and 46-0-0-0) was applied through mid-row banding at a depth of 5.1 to 6.4 cm roughly 15 cm from the seed row. The application of nitrogen with mid-row banding was utilized for: barley, canaryseed, canola and durum wheat crops. All other fertilizer was placed with the seed (Table 2).

In-crop weed management was achieved using registered post-emergence herbicides, with selection based on the crop stage and weed species present in each field. Each spraying event consisted of uniform application at a recommended rate for the whole field. Insects were deterred with seed treatment prior to seeding, and with in-crop spraying using registered insecticide products at a recommended rate for the whole field. All crops were harvested at maturity prior to autumn frost in the growing year they were planted.

Observational design

Seeding data was obtained through shapefiles comprised of spatial polygons created by a X30® console (Topcon, Tokyo, Japan). Yield information was acquired through spatial point

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shapefiles exported from a GreenStar 3 2630® display (John Deere, Moline, USA). This system was calibrated for accuracy using a full hopper of dry grain (John Deere & Company 2012). Records from these two sources were merged using a point-in-polygon spatial join (Pebesma and Bivand 2005). In total, 4,268,459 observation points were obtained with attribute information. Data was cleaned using a standard deviation filter, minimum swath width filter and manual filter. Records excluded were: (i) those with a yield two standard deviations above or below the mean for each crop type in each field; (ii) those from swaths that were 30% narrower than adjacent swaths; and (iii) those likely from headlands with a yield less than 5.6 kg ha^{-1} (Sudduth and Drummond 2007). This resulted in 3,627,023 valid observation points. Latitude coordinates were recorded to five decimal places and longitude coordinates to four decimal places for each observation in decimal degrees. Precision was roughly 2 m in latitude and 12 m in longitude (Wieczorek et al. 2004).

To alleviate spatial autocorrelation and difficulties arising from analysis with too large a number of data points, a sampling pattern of observations was utilized (Plant 2012). A stratified random sample was taken with 1000 observations for each combination of field, crop type and year. From a field with the average area of 56.1 hectares seeded to a single crop in a particular year, approximately 17 to 18 observations were collected from each hectare in this sampling scheme. The exception to the sampling design was a durum wheat field in which seeding data was recorded for 1.08 hectares. From this particular field, a sample of 39 observations was taken. This resulted in a final sample of 122,039, of which: 3,000 were for barley, 6,000 for canaryseed, 17,000 for canola, 46,000 for lentil and 50,039 for durum wheat crops.

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Statistical analysis

Statistical analysis was conducted separately for each crop using the MCMCglmm package (Hadfield 2010) in R version 3.5.1 (R Core Team 2018) that utilized Markov chain Monte Carlo (MCMC) methods. Random intercept models from the Gaussian family that included fixed and random effects were run for 277,800 iterations. A 10% burn-in and thinning interval of 125 were utilized to reduce autocorrelation. This yielded an effective sample size of 2,000 per parameter in the posterior distribution. Proper diffuse priors with a normal distribution ($\mu = 0$, $\sigma^2 = 10^{10}$) were specified for the fixed effects (McDonald et al. 2016). Priors with an inverse Wishart distribution ($V = 1$, $\nu = 1$, alpha-$\mu = 0$, alpha-$V = 0$) were specified for the random effects and residuals ($V = 1$ and $\nu = 0$). Markov chains converged and autocorrelation was less than 0.1.

The response variable of each random intercept model was dry yield in absolute value. Fixed effects were explanatory variables that are regularly modified at planting. These included rates (in kg ha^{-1}) of: seed, inoculant, nitrogen, phosphorus, potassium chloride and sulphur. Random effects were explanatory variables which comprised a random classification from a larger population. These consisted of: field, crop cultivar, crop planted in previous year, planting year, combine machine used for harvest, geographic coordinates of observation within field and the elevation. As is the custom in the Bayesian framework (Thomas et al. 2007), all explanatory variables of interest that denoted fertilizer application were fitted in the applicable model for crop type to stabilize parameter coefficients. This also helped to control for confounding that arose from nutrients being in a combined fertilizer blend. The deviance information criterion (DIC) was used to evaluate models for the best fitting covariance structure in the selection of priors. The limit for significance was MCMC P-value < 0.05.

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Results

Nutrient inputs at planting

Table 3 shows the mean yield and application amounts of seed and fertilizer nutrients at planting for: barley, canaryseed, canola, lentil and durum wheat crops over the study period. Mean yield varied from a low of 1230 kg ha^{-1} for canaryseed, to a high of 4360 kg ha^{-1} for barley. With regard to durum wheat, the mean seeding rate was 85.8 kg ha^{-1} with: 88.9 kg ha^{-1} of nitrogen, 33.0 kg ha^{-1} of phosphorus and 14.0 kg ha^{-1} of potassium chloride applied. Canola crops had the lowest mean seeding rate, at 5.0 kg ha^{-1}. Canola was also the only crop with sulphur applied, at 16.1 kg ha^{-1}. Regarding nitrogen, lentil crops had the lowest mean fertilizer use at 5.1 kg ha^{-1}, while canola had the highest at 98.3 kg ha^{-1}. No potassium chloride was applied when seeding canola, although canaryseed had the highest application amount at 14.8 kg ha^{-1}. As the only pulse grown, granular inoculant was applied on lentil crops at a mean rate of 4.5 kg ha^{-1}.

Crop yields and nutrient management response

As hypothesized, evidence of a yield response from variation in mean fertilizer rates at planting was observed among lentil and durum wheat crops in the random intercept models (Table 4). The intercept from these models represent the expected mean crop yield. For canola crops, no deviation from the observed mean rates of nutrients or seed applied at planting (Table 3) was associated with a change in mean yield (Table 4). Regarding the other crop types, optimizations were suggested from the models to improve yield or conserve inputs. An increase in seed rate of 1 kg ha^{-1} from the mean amount was associated with a yield increase of 4.6 kg ha^{-1} in canaryseed crops (Table 4). For each additional kg ha^{-1} of potassium chloride added at

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planting for durum wheat, mean yield increased by 364.8 kg ha^{-1}. Yield decline associated with high fertilization rates were also conveyed from the model output. Above the mean amount, each kg ha^{-1} of nitrogen at planting was associated with a 4.2 kg ha^{-1} decrease in lentil yield. For durum wheat crops, each additional kg ha^{-1} of phosphorous above the mean amount was associated with a 153.3 kg ha^{-1} decrease in yield.

Information on the proportion of variation in crop yield attributable to a random effect were obtained from the intraclass correlation coefficient (ICC) of the random intercept models (Table 4). Among durum wheat crops, approximately 24% of the variation in yield was attributable to field. High yield variation was due to the geographic coordinate of observation within field, at roughly 46%. The random effect of cultivar had negligible impact (0%) on yield for the two crop types where multiple cultivars were seeded (canola and lentil). Differences in yield attributable to combine machine varied from a low of 0% for durum wheat, to a high of 11% for canaryseed. Yield differences due to planting year varied from a low of 0% for canola, to a high of 28% for lentil crops. Yield variation that was attributable to crop type grown in the previous year varied from a low of 0% for canaryseed, to a high of 14% for canola.

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Discussion

Fertilization, seed rate and crop production

The present study suggests that the mean rates of seed and fertilizer utilized at planting for canola crops were suitable with respect to grain yield for this farming operation, and were in accordance with recommended rates. However, optimization can be made in the managing of other crops. Regarding canaryseed, response at this farming operation suggests that an additional 4.6 kg ha^{-1} in yield was obtained for each kg ha^{-1} increase in seed above the mean rate. It should

be noted that the mean canaryseed yield of 1230 kg ha^{-1} from a seeding rate of 28.9 kg ha^{-1} is in close agreement through linear extrapolation of the statistical model to the estimated maximum yield of 1310 kg ha^{-1} from a seeding rate of 45 kg ha^{-1} that was observed in experimental field plots (May et al. 2012). The high yield variability of canaryseed within fields has also been observed in other studies (Xyntaris and Hucl 2015).

There was evidence of redundant nitrogen fertilization at planting being associated with decreased yield in lentil crops. It is possible that a residual effect of nitrogen accumulation in soil from previous planting years may have occurred, but it is more plausible that the safe application rate for nitrogen with seed placement was exceeded. As a pulse, lentil plants symbiotically fix nitrogen from the atmosphere (Hossain et al. 2017), with higher amounts of nitrogen fixation stimulated by organic matter (Yang et al. 2015). Interestingly, a longitudinal study found residual nitrate accumulation at a field plot near Swift Current to increase only marginally after higher rates of nitrogen application, although grain yield increased (Grant et al. 2016). This suggests that attempts to enhance residual soil fertility are more limited in a semiarid agroecosystem, albeit higher yields are possible. With regard to yield for the farming operation under study, the mean lentil harvest of 1410 kg ha^{-1} over the period from 2015 to 2018 was less than that observed at an experimental site in the Swift Current region from 2008 to 2010 (Hossain et al. 2017).

Acknowledgement is made that the maximum safe application rates for phosphorus and potassium chloride placed with seed at planting were exceeded in this observational study. Lentil crops had a mean combined application rate of 31.1 kg ha^{-1} for phosphorus and potassium chloride; this is over the recommended maximum safe rate of 22.4 kg ha^{-1}. At 49.9 kg ha^{-1}, the safe application rate of 33.6 kg ha^{-1} for combined phosphorus and potassium chloride placed

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with seed was also surpassed for canaryseed. To why the maximum safe rates of fertilizer application were exceeded is complex and multifaceted. Reasons include the challenge of knowledge dissemination in recommended practice between agronomist and producer, stresses faced by farmers in utilizing a common fertilizer blend for multiple crop types and the limitation of seeding equipment. However, there are economic and time advantages of direct-seeding with high amounts of fertilizer placed with seed in one-pass. Based on hearsay starting around 2012, the farming operation under study embarked on remedial fertilizer application, with a particular focus on phosphate (placed with seed) in wetter seeding conditions. Although not a justification to exceed safe application rates, the heavy clay found on this farming operation enables higher amounts of fertilizer to be placed with seed (Agriculture Knowledge Centre 2019b).

A more explicit association between grain yield and inorganic fertilizer use may have been observed if a custom fertilizer was applied at planting for each crop type that excluded superfluous nutrients. For example, a blend containing phosphorus without nitrogen may have been beneficial for lentil yield. However, procurement and storage of additional fertilizer blends is not convenient for the producer to implement. The relevance of observational research highlights tendencies that occur in action, with deviations from recommended practice addressed. Although four-year crop rotations are stressed on the Canadian Prairies (Bainard et al. 2017), many farming operations rely heavily on a lentil-wheat rotation, such as this case study. Other inconsistencies include sources of measurement error. It is of interest to note that up to 11% of the variation in canaryseed yield, as denoted by the intraclass correlation coefficient, was attributable to the combine machine used at harvest. This may be due to differences in operator behavior between machines, or the calibration of the yield monitoring instrument.

This study demonstrated a unique approach, in that its observational design utilized

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precision agriculture over many hectares and affirmed recommendations for farming practice that were obtained mostly from experimental field plots. It should be noted that inferences drawn from randomized controlled trials are more powerful and direct in establishing causation, and are held in higher regard than those obtained from observation. However, there are confounding variables that are difficult to exclude in practice that are often ignored in experimental designs, such as characteristics of a particular farming implement or readily-available fertilizer blend in a geographic area. These factors have the potential to introduce bias in the translation of recommended practice, and are present in every farming operation. Although undesired, sources of bias in an observational design can be acknowledged and partially controlled for through the inclusion of confounding variables in a statistical model. Observational research with its caveats has a role in validating robust science obtained from experiment in field plot studies.

The present study was an observation from a single farming operation in a single agroecoregion. Instances of crop spraying were not adjusted for in the statistical models. With knowledge of the farming operation, it is known that each spraying event was applied uniformly across the entire field. Upon examination of the intraclass correlation coefficient, the explained variability in yield was higher within fields than between fields for most crop types over the study period. This suggests that mean yield was affected less by ancillary farming events applied uniformly over the field, such as crop spraying, than events with differential effects happening within the field.

Although having an impact on grain yield, rainfall amount during the growing season and organic carbon content in soil were also uncontrolled for in the analyses. Higher amounts of variation (Table 4) in lentil yield (28%) was attributable to planting year and elevation (8%) than the other crop types. This implies that pulses were more sensitive to climatic or environmental

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differences between growing seasons. Soil test information was also unavailable for the farming site.

Conclusion

Findings from this observational study with regard to fertilization on crop yield validate recommendations obtained from experimental field plots for agronomic practice. Evidence of a nitrogen effect associated with diminished yield in annual lentil crops was observed beyond a mean application of 5.1 kg ha^{-1}, when controlling for other factors. This suggests that a fertilizer blend excluding nitrogen may be beneficial for lentil crops at planting when *Rhizobium* inoculation is effective. Placement of phosphorus with seed above 33.0 kg ha^{-1} was associated with decreased yield in durum wheat. Although residual soil potassium is high in the Canadian Prairies, observation suggests that supplemental potassium chloride over 14.0 kg ha^{-1} was beneficial for yield in durum wheat crops. Greater variation in grain yield was observed within fields than between fields for this farming operation. This observational study suggests that higher yield may be achieved through variable rate fertilization and adherence to safe rate recommendations of fertilizer placed in the seed row. Optimization of individual farming operations could be achieved by using a similar approach to the analysis of farm-scale practices, helping to identify efficiencies that may otherwise go unnoticed.

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Acknowledgement

The author wishes to thank Wayne Pittman for his encouragement and support in pursuing this research.

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Table 1. Crops grown by field at the farming operation: 2014-2018.

Field	Planting year and crops grown				
	2014	2015	2016	2017	2018
1	Canaryseed	Canola	Wheat	Lentil	Wheat
2	Canaryseed	Lentil	Canaryseed	Lentil	Wheat
3	Wheat	Lentil	Wheat	Lentil	Canola
4	Lentil	Wheat	Lentil	Wheat	Lentil
5	Wheat	Lentil	Canaryseed	Canola	Wheat
6	Lentil	Wheat	Lentil	Wheat	Lentil
7	Wheat	Lentil	Wheat	Lentil	Canola
8	Canola	Wheat	Lentil	Canola	Wheat
9	Canaryseed	Canola	Wheat	Lentil	Canola
10	Wheat	Canola, Lentil[a]	Wheat	Lentil	Wheat
11	Lentil	Wheat	Lentil	Canola	Wheat
12	Wheat	Lentil	Wheat	Lentil	Canola
13	Lentil	Wheat	Lentil	Wheat	Lentil
14	Wheat	Lentil	Wheat	Lentil, Barley[a]	Canola
15	Lentil	Wheat	Lentil	Wheat	Lentil
16	Canola	Wheat	Lentil	Wheat	Lentil
17	Canaryseed	Lentil	Wheat	Canola	Wheat
18	Lentil	Wheat	Lentil	Canola	Wheat
19	Wheat	Lentil	Wheat	Canola	Wheat
20	Lentil	Wheat	Lentil	Barley	Lentil
21	Wheat	Lentil	Wheat	Barley	Lentil
22	Lentil	Wheat	Lentil	Canola	Wheat
23	Wheat	Lentil	Wheat	Canola	Wheat
24	Lentil	Wheat	Canaryseed	Lentil	Wheat
25	Lentil	Wheat	Canaryseed	Lentil	Wheat
26	Wheat	Lentil	Wheat	Canaryseed	Lentil
27	Wheat	Lentil	Wheat	Canaryseed	Lentil
28	Lentil	Wheat	Lentil	Wheat	Lentil
29	Lentil	Wheat	Lentil	Wheat	Canola
30	Wheat	Wheat	Lentil	Wheat	Lentil
31	Wheat	Lentil	Wheat	Lentil	Wheat

Note: [a]Split cropping

Table 2. Cultivar of crops grown and fertilizer blends at the farming operation: 2015-2018.

Cultivar of crops grown				
Barley	Canaryseed	Canola	Lentil	Wheat
CDC Copeland	CDC Calvi	L140P	CDC Greenland	AC Brigade
		L156H	CDC Greenstar	
		L233P		

Fertilizer blends (percentage N-P-KCl-S) utilized and placement	
Mid-row	With seed
41-0-0-4	8-37-16-0
46-0-0-0	8-38-16-0
	11-52-0-0
	15-30-0-0
	21-0-0-4

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Table 3. Crop yield and input rates (kg ha-1).

	Crop yield and inputs in kg ha^{-1}				
	Barley (n = 3,000)	Canaryseed (n = 6,000)	Canola (n = 17,000)	Lentil (n = 46,000)	Wheat (n = 50,039)
Mean (SD[a])					
Yield	4360 (1010)	1230 (660)	2160 (500)	1410 (700)	3310 (1290)
Seed Rate	83.9 (16.6)	28.90 (6.3)	5.0 (2.0)	112.3 (30.1)	85.8 (16.8)
N Rate	71.8 (21.3)	55.69 (13.1)	98.3 (21.7)	5.1 (2.5)	88.9 (17.3)
P Rate	30.2 (5.9)	35.09 (7.8)	4.6 (10.4)	23.8 (7.6)	33.0 (6.3)
KCl Rate	12.7 (2.5)	14.78 (3.3)		7.3 (4.8)	14.0 (2.7)
S Rate			16.1 (7.7)		
Inoculant Rate				4.5 (3.5)	

Note: [a]Standard deviation.

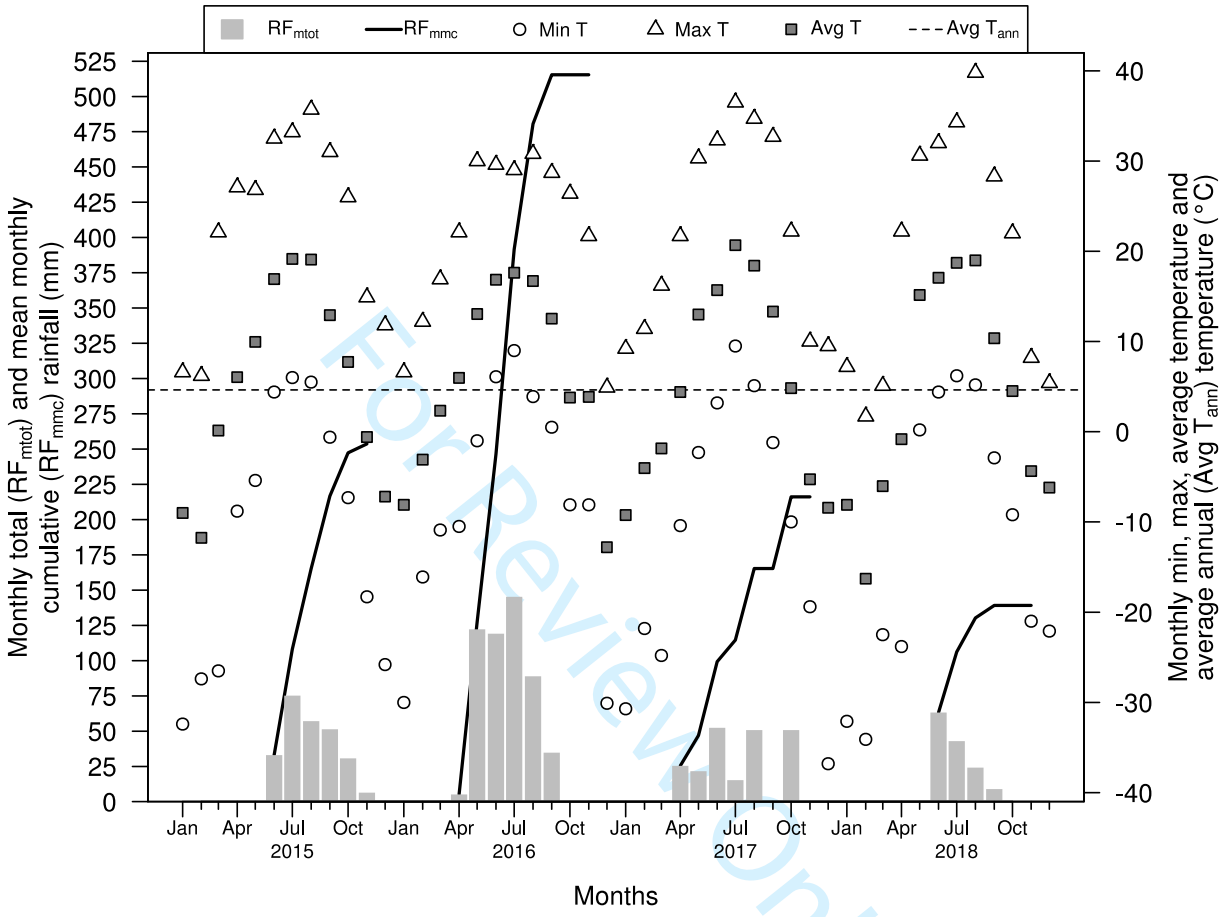
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Table 4. Crop yield (kg ha-1).

	Yield of crops grown in kg ha^{-1}				
	Barley	Canaryseed	Canola	Lentil	Wheat
Fixed Effects					
β (95% HPDI[a])					
(Intercept)	4455.0	961.4	2063.2	1495.1	3644.0
Seed Rate	-3.2 (-5.6, -0.8)**	4.6 (2.5, 6.8)***	0.9 (-2.0, 4.2)	0.1 (-0.1, 0.3)	-0.8 (-1.5, -0.1)**
N Rate	1.9 (-0.5, 4.2)	0.9 (-0.6, 2.4)	-0.1 (-0.6, 0.3)	-4.2 (-6.2, -2.0)***	0.5 (-0.2, 1.3)
P Rate	-320.1 (-2190.5, 1606.6)	-499.3 (-1289.3, 226.4)	0.9 (-1.0, 2.8)	-0.2 (-1.6, 0.9)	-153.3 (-296.9, -17.9)*
KCl Rate	773.2 (-3787.2, 5216.7)	1182.6 (-542.3, 3052.3)		4.5 (1.5, 7.5)*	364.8 (25.5, 684.3)*
S Rate			-0.1 (-2.3, 2.1)		
Inoculant Rate				2.3 (1.1, 3.5)***	
Random Effects					
ICC[b] (95% HPDI[a])					
Field	0.00 (0.00, 0.22)	0.13 (0.00, 0.44)	0.16 (0.04, 0.31)	0.07 (0.02, 0.17)	0.24 (0.08, 0.36)
Cultivar			0.00 (0.00, 0.00)	0.00 (0.00, 0.01)	
Previous Crop	0.10 (0.00, 0.78)	0.00 (0.00, 0.00)	0.14 (0.03, 0.59)	0.02 (0.00, 0.22)	0.10 (0.02, 0.63)
Combine	0.06 (0.00, 0.71)	0.11 (0.04, 0.83)	0.02 (0.00, 0.38)	0.04 (0.00, 0.51)	0.00 (0.00, 0.10)
Planting Year			0.00 (0.00, 0.00)	0.28 (0.06, 0.71)	0.04 (0.00, 0.26)
Geocoordinates	0.40 (0.04, 0.56)	0.46 (0.07, 0.55)	0.40 (0.14, 0.48)	0.22 (0.05, 0.33)	0.20 (0.07, 0.25)
Elevation	0.00 (0.00, 0.00)	0.06 (0.01, 0.15)	0.00 (0.00, 0.06)	0.08 (0.02, 0.13)	0.07 (0.02, 0.10)

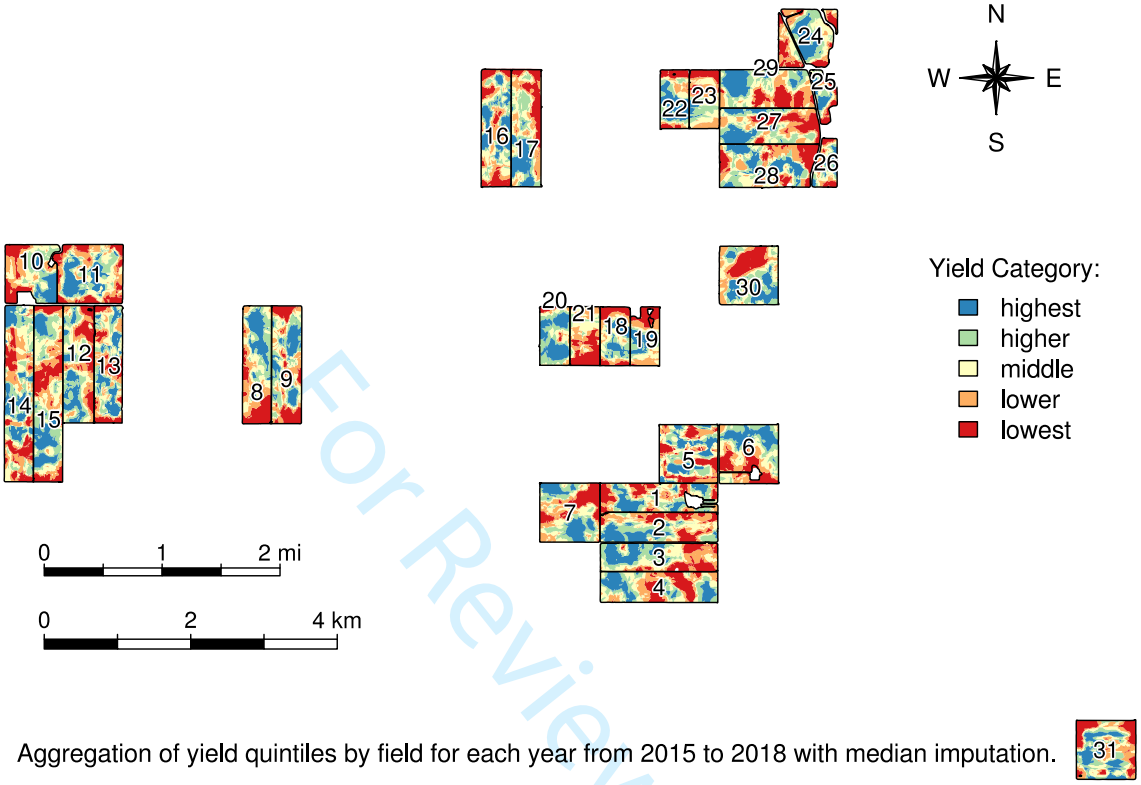
Note: Markov chain Monte Carlo (MCMC) P-value significance at P < 0.1 (†), P < 0.05 (*), P < 0.01 (**), and P < 0.001 (***).
[a]Highest posterior density interval.
[b]Intraclass correlation coefficient.

Fig. 1. Monthly total, mean monthly cumulative rainfall at the farming operation site; monthly minimum, maximum and average temperature at Swift Current, Saskatchewan (WMO ID: 71142): 2015-2018.



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Fig. 2. Spatial overview of grain yield by field at the farming operation: 2015-2018. Figure was created using R version 3.5.1.



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